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Decision making model for lifecycle assessment of lithium-ion battery for electric vehicle – A case study for smart electric bus project in Korea

Sabai Thein, Yoon Seok Chang*

Ubiquitous Technology Application Research Center, School of Air Transport and Logistics, Korea Aerospace University, 76 Hanggongdaehang-ro, Goyang 412-791, Republic of Korea

HIGHLIGHTS

- This research presents a case study from e-bus development project in Korea.
- Markov Decision Process model are applied for the product lifecycle management of Li-ion EV battery.
- Decisions with related cycle times are provided by considering SOH of each battery.
- Research finds measures of the battery performance and life reliability & probability.

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ABSTRACT

Lithium-ion (Li-ion) battery is part of our everyday life. There are many automobiles invented today that operates by Li-ion batteries. The issue with batteries is that they lose capacity and reliability over time as they are charged and discharged. This paper introduces a lifecycle assessment system for Li-ion EV battery considering the condition of each battery which helps decision making. The proposed research concerns not only for the ad-hoc condition but also regular condition of the Li-ion EV battery. We apply the Markov Decision Process (MDP) with selected policies for the measurement of each stage probability. The result shows that we could monitor product aging status with the proposed algorithm. It also shows that the calculated product life span was longer than the general warranty time period.

1. Introduction

Product lifecycle theory has been a key principle in the studies of technical innovation over the last 20 years and is promoted by leading management theorists as a tool for strategic decision making [1]. Making the 'right' decisions at each stage in a product lifecycle is important to the healthy, sustainable development of manufacturing industry. With the growing concern about the global warming and environmental issues, sustainable manufacturing and efficient resource utilization are gaining popularity with significant potential in theoretical study as well as industrial applications [2].

* Corresponding author.
E-mail addresses: sabaithein@kau.ac.kr (S. Thein), yoonchang@kau.ac.kr (Y. S. Chang).

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Sustainable product lifecycle systems gain increasing attention because of cost competition, resource constraints and environmental issues. Short lifecycle products, such as consumer and defense electronics, are of particular concern [1,2].

The lifecycle assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and material usage and environmental releases. It assesses the impact of that energy and material uses, and release on the environment, and also evaluates and implements opportunities to effect environmental improvements. The assessment included the entire lifecycle of a product, process or activity, encompassing extracting and processing raw materials, manufacturing transportation, and distribution use/re-use/maintenance, recycling and final disposal [3].

Because the life of battery is affected by many factors such as work environment and charge–discharge characteristics, it hardly reaches the value of cycle life claimed by suppliers. If the

replacement is too late, it will affect the reliability of system. If we could accurately understand the life span status of storage battery, we can undoubtedly get the best compromise of economy and reliability [4,5]. Battery management system (BMS) monitors the state of battery, measures the most important operating parameters and protects the battery against any damage. Integrated Battery Management System increases the safety of the system and allows the estimation of state of health. The use of battery management system will lead to and increased life time and safer operation of the battery [6,7].

Battery damage occurs due to a number of reasons, such as overcharging and over-depleting, etc. Battery operation is dynamic and its performance varies significantly with age. An important aspect of battery diagnostics is the state of health (SOH) of battery which is a measure of the battery ability to store energy and to deliver power. Battery diagnostics track the degradation of battery performance to estimate battery SOH [8].

This research considers the condition monitoring techniques for battery aging system. Typical condition monitoring system consists of 4 parts: sensor; data acquisition; fault detection; and diagnosis. A data acquisition system (DAS) converts physical conditions into digital form, for further storage and analysis. In this research, data acquisition is used to collect data for calculating the battery SOH. We applied EV battery usage report file to calculate the battery state of health [9–11].

2. Problem formulation

This paper has two parts:

- EV battery SOH calculation by using EV battery usage report.
- EV battery decision making process which is dependent on the current battery status. We applied condition monitoring techniques and Markov Decision Process (MDP) in this research.

Effective vehicular power management requires accurate and reliable knowledge of the battery state. The battery state is represented by state-of-charge (SOC) and SOH and battery performance is dependent upon the SOC and SOH of the battery. In order to be able to detect limited battery functionality, it is essential to measure or estimate these properties [8,12–15].

2.1. State of charge (SOC)

The battery state of charge (SOC) represents the stored power and energy available. SOC is the percentage of the actual amount of charge compared with the full charge. The battery SOC is a key factor in the battery management system (BMS) [13,16,17]. Battery SOC defines the remaining charge as a percentage of the stored charge in a fully charged battery. It cannot be measured during vehicle operation and can be obtained only through onboard estimation [13,15,18–20].

$$\mathrm{SOC} = \frac{\text{Actual amount of charge}}{\text{amount of total charge}} * 100\% \tag{1}$$

2.2. State of health (SOH)

The State of Health (SOH) is a “measurement” that provides an indication of the performance which can be expected from the battery in its current condition. SOH provides an indication of how much the battery has been consumed and how much remains before it must be replaced. It takes into account factors such as charge acceptance (charge/discharge cycles of the battery usage), internal resistance, voltage, age or cycle life and remaining cycle life [5,21].

In this paper, we used SOH $= (C_i/C_0)*100\%$ [5] for SOH (where, C_i is the ith capacitance measurement in time and C_0 is the initial value) and consider the factor of EV battery temperature, passenger weight and current life time of the battery.

We assume the battery temperature, passenger weight and current battery life are constants (i.e., K).

$$\mathrm{SOH} = \left(\frac{C_i}{C_0}\right) * T_\mathrm{b} * \mathrm{W_P} * \mathrm{L_{cb}} * 100\%$$

$$\mathrm{SOH} = \left(\frac{C_i}{C_0}\right) * K * 100\% \tag{2}$$

where, T_b = battery temperature, W_P = passenger weight, L_cb = current battery life, K = constant.

3. Markov Decision Process (MDP)

Markov Decision Process (MDP) is a discrete time stochastic control process and extension of Markov chains which allow nondeterministic choice. It is generally solved by linear programming or dynamic programming. Discrete set of states representing possible configurations of the system being modeled by the transitions between states occurs in discrete time-steps. Each state has a nondeterministic choice between several discrete probability distributions over successor states. It is a choice of a policy π that will maximize some cumulative function of the random rewards [22].

Decision policy (action) is important in Markov Decision Process. A function π that specifics the action $\pi(S)$

$$\pi(S) = \sum_{t=0}^{\infty} \gamma^t R_{a_t}(S_t, S_{t+1}) \tag{3}$$

where, $a_\mathrm{t} = \pi(S_\mathrm{t})$ and γ is the discount factor and satisfies $0 \le \gamma < 1$.

For example, $\gamma = 1/(1+r)$ when the discount rate is r. γ is typically close to 1 [22,23].

Formally, an MDP M is a tuple (S,s_init, **Steps**, L), where: S is a finite set of states (“state space”), $s_\mathrm{init} \in S$ is the initial state, Steps : $S \to 2^{\mathrm{Act} \times \mathrm{Dist}(S)}$ is the transition probability function where, Act is a set of actions and Dist(S) is the set of discrete probability distributions over the set S. L: $S \to 2^{\mathrm{AP}}$ is a labeling with atomic propositions. Notes: Steps(s) is always non-empty, i.e. no deadlocks, the use of actions to label distributions is optional [22,23].

$\mathbf{P_a}(\mathbf{s}, \mathbf{s'}) = \mathbf{Pr}(\mathbf{s_{t+1}} = \mathbf{s'} | \mathbf{s_t} = \mathbf{s}, \mathbf{a_t} = \mathbf{a})$ is the probability for action in state S at time t to lead to state S' at time $t+1$ [22,23].

3.1. Markov Decision Process (MDP) model for Li-ion EV battery

In Markov decision support model for EV battery system (Fig 1.), let S be the state $s \in S = \{1,2,\ldots n\}$, where s is the state space. Let $A(s)$ be the action space of state s, and $a \in A(s)$ be one such action.

Then, the entire action space is $A = U_{s \in S} A(s)$.

Let, L: $S \to A$ be the policy, $L \in L$, where L is the set of all policies.

Let, $c(s,a)$: $S \times A \to R$ be the cycle times of action a at state s.

Let, $h(s,a)$: $S \times A \to H$ be the state of health of action a at state s.

We assume that there are 6 states in total: battery aging stage S_0; Inspection stage S_I; three decision process stages of Reuse state S_Reuse; Remanufacturing state S_Remfc; Recycling state S_Recyc; and finally failure stage F or disposal stage of S_Dis.

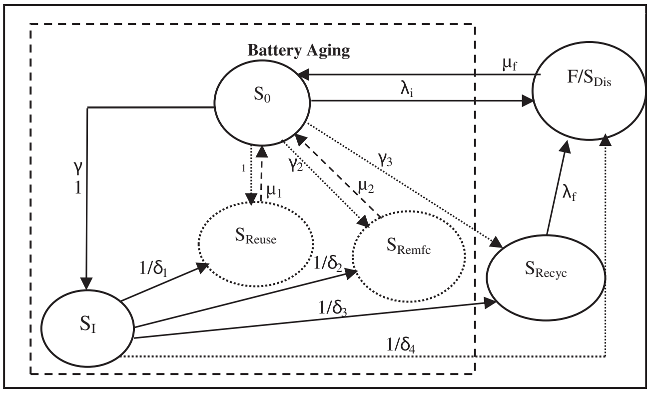


Fig. 1. EV battery Markov Decision Process model.

3.2. Problem analysis and Markov decision policy for EV battery

Decision policy (action) is important in Markov Decision Process.

A function π that specifics the action $\pi\ (S)$

Where, we choose $a_t = \pi\ (S_t)$

$$a_t = f(\pi(S_t x)) = \begin{Bmatrix} x \\ x_1{}' \\ x_2 \\ x_3 \end{Bmatrix} \quad \begin{matrix} X < 0 \\ X_i \geq 0 \end{matrix} \tag{4}$$

Some of the manufacturer (e.g. Global Electric Vehicles, Nissan leaf, etc.) started to consider the remanufacturing of Li-ion EV battery when it reaches 1000 cycle times or 80% of capacity. And when it reach to the 70% of capacity, the battery should be dropped to the second life and recycling [24,25]. According to Smith Electric Vehicles, however, some battery might still have a minimum of 80% capacity even after 3000 cycles [26].

We assumed following decisions policy in this system:

X_0 = Reuse SOH % ($80 \leq x_0 \leq 100$); X_1 = Remanufacturing SOH % ($70 \leq x_1 < 80$);

X_2 = Recycling SOH % ($50 \leq x_2 < 70$); X_3 = Disposal SOH % ($x_3 < 50$).

This system has 4 actions and decision policies (Table 1):

- Reuse: use an item more than once. i.e. the item is used again for the same function;
- Remanufacturing: the repair and the replace of some parts to be as good as usual. This action is done after parts are used. The product repair and overhaul or replacement of worn out/obsolete components and modules belongs to remanufacturing;
- Recycling: the process of used materials (waste) into new products to prevent waste of potentially useful materials. This action reduces the consumption of fresh raw materials.
- Disposal: the action of systematic destruction or transformation of systematic garbage of unusable thing.

Table 1
Actions of EV battery Markov Decision Process policy.

No.	Term	Policy rules	Action
1.	Reuse	SOH % ($80 \leq x_0 \leq 100$)	X_0
2.	Remanufacturing	SOH % ($70 \leq x_1 < 80$)	X_1
3.	Recycling	SOH % ($50 \leq x_2 < 70$)	X_2
4.	Disposal	SOH % ($x_3 < 50$)	X_3

3.3. Markov Decision Process policy module algorithm

Firstly, we read the usage data from battery report file to get the data of capacity, cycle time, battery temperature, passenger weight and current battery life for each battery. After that we calculated the SOH of each battery then make a decision considering our decision making policies. Before decision making, we have to check the following three cases: ad-hoc; error; and checking of battery condition.

Table 1 shows Markov Decision Process policy rules for EV battery and Table 2 shows example algorithm of Markov Decision Process module for EV battery. For example, if "ad-hoc" is true, battery will be needed to do some actions (e.g. remanufacturing, recycling and disposal) considering the conditions.

3.4. Probability performance measurement for each stage

From [22],

$$\mathrm{Det}(A) = \sum_{j=1}^{n} (-1)^{i+j} a_{i,j} M_{i,j} = \sum_{i=1}^{n} (-1)^{i+j} a_{i,j} M_{i,j} \tag{5}$$

With Markov decision model, we can find each step flow as the following:

$$\text{Steps} = \begin{bmatrix} 0 & \gamma & \gamma_1 & \gamma_2 & \gamma_3 & \lambda_i \\ 0 & 0 & 1/\delta_1 & 1/\delta_2 & 1/\delta_3 & 1/\delta_4 \\ \mu_1 & 0 & 0 & 0 & 0 & 0 \\ \mu_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu_3 & \lambda_f \\ 0 & 0 & 0 & 0 & 0 & \mu_f \end{bmatrix} \tag{6}$$

The expressions of all of the steps in Equation (6) are as follows.

For state S_0, there are moving decision to S_I (inspection action), S_{Reuse} (action x), S_{Remfc} (action x_1), S_{Recyc} (action x_2), S_{Dis} (action x_3):

$$\begin{aligned} \mathrm{Step}(S_0) = \Big\{ & (\text{inspection}, S_I \to \gamma), (x_{0,} S_{Reuse} \to \gamma_1), \\ & \times \left(x_{1,} S_{Remfc} \to \gamma_2\right), (x_{2,} S_{Recyc} \to \gamma_3), (x_{3,} S_{Dis} \to \lambda_i) \Big\} \end{aligned} \tag{7}$$

For inspection state $S_{I,}$ there are movement with decision policy (action), move to S_{Reuse} (action x), S_{Remfc} (action x_1), S_{Recyc} (action x_2), S_{Dis} (action x_3):

Table 2
Algorithm for EV battery Markov Decision Process.

```
Begin
 READ Battery usage report file;
 CALCULATE Battery SOH;
 CHECK battery SOH for Decision Making
 Begin
 IF (battery status (Ad-hoc) Alarm is true) THEN CHECK Remanufacturing/Recycling/Disposal
   ELSE (ERROR)
    IF ((Battery SOH >100%) or (Battery SOH <= 0) )THEN begin
                    ERROR;
    Halt;;  end;
 {Action X0}
 IF ((Battery SOH <=100%)and (Battery SOH >= 80%))THEN Go to Reuse Process;
    ELSE{Action X1}
 IF ((Battery SOH<80%) and (Battery SOH >=70%)) THEN Go To Remanufacturing Process;
   ELSE{Action X2}
 IF ((Battery SOH < 70%) and (Battery SOH>=50%)) THEN Go To Recycling Process;
    ELSE {Action X3}
 IF(Battery SOH>=50%) THEN Go To Disposal Process;
 End; Halt (Brake);
  Re-use Process;
   Begin (Remanufacturing Process)
 IF Testing OK THEN Go to Re-use process
  ELSE Go to Recycling;      End;
    Recycling Process;
 IF (battery SOH < 50%) THEN Go to Disposal process;
   Disposal Process;
 End.
```

$$\mathrm{Step}(S_{\mathrm{I}}) = \Big\{(x_0, S_{\mathrm{Reuse}} \to 1/\delta_1), \Big(x_1, S_{\mathrm{Remfc}} \to 1/\delta_2\Big), \times (x_2, S_{\mathrm{Recyc}} \to 1/\delta_3), (x_3, S_{\mathrm{Dis}} \to 1/\delta_4)\Big\} \quad (8)$$

$$\text{For state } S_{\mathrm{Reuse}}, \text{ move to state } S_0 : \mathrm{Step}(S_{\mathrm{Reuse}}) = \{(x_0, S_0 \to \mu_1)\} \quad (9)$$

$$\text{For state } S_{\mathrm{Remfc}}, \text{ move to state } S_0 : \mathrm{Step}\Big(S_{\mathrm{Remfc}}\Big) = \{(x_1, S_0 \to \mu_2)\} \quad (10)$$

$$\text{For state } S_{\mathrm{Recyc}}, \text{ move to state } S_{\mathrm{Dis}} : \mathrm{Step}(S_{\mathrm{Recyc}}) = \Big\{\Big(x_2, \Big[S_{\mathrm{Dis}} \to \mu_{\mathrm{f}}, S_{\mathrm{Recyc}} \to \mu_3\Big]\Big)\Big\} \quad (11)$$

$$\text{For state } S_{\mathrm{Dis}}, \text{ move to state } S_0 : \mathrm{Step}(S_{\mathrm{Dis}}) = \Big\{\Big(x_3, S_{\mathrm{Dis}} \to \mu_{\mathrm{f}}\Big)\Big\} \quad (12)$$

From Equations (7)–(12), we drive out the probabilities for each stage decision action as follows:

$$\cdot\ Px_0(S_{\mathrm{I}}, S_{\mathrm{Reuse}}) = \Pr\Big(S_{\mathrm{I}(t+1)} = S_{\mathrm{Reuse}} | S_{\mathrm{I}(t)} = S_{\mathrm{I}}, x_{\mathrm{t}} = x_0\Big) \quad (13)$$

$$\cdot\ Px_1\Big(S_{\mathrm{I}}, S_{\mathrm{Remfc}}\Big) = \Pr\Big(S_{\mathrm{I}(t+1)} = S_{\mathrm{Remfc}} \Big| S_{\mathrm{I}(t)} = S_{\mathrm{I}}, x_{\mathrm{t}} = x_1\Big) \quad (14)$$

$$\cdot\ Px_2(S_{\mathrm{I}}, S_{\mathrm{Recyc}}) = Pr\Big(S_{\mathrm{I}(t+1)} = S_{\mathrm{Recyc}} | S_{\mathrm{I}(t)} = S_{\mathrm{I}}, x_{\mathrm{t}} = x_2\Big) \quad (15)$$

$$\cdot\ Px_3(S_{\mathrm{I}}, S_{\mathrm{Dis}}) = Pr\Big(S_{\mathrm{I}(t+1)} = S_{\mathrm{Dis}} | S_{\mathrm{I}(t)} = S_{\mathrm{I}}, x_{\mathrm{t}} = x_3\Big) \quad (16)$$

After we substituted the rate $\mu_1, \mu_2, \mu_{\mathrm{f}}, \lambda_{\mathrm{i}}, \lambda_{\mathrm{f}}, \delta, \delta_1, \delta_2, \delta_3, 1/\delta_1, 1/\delta_2, 1/\delta_3$ and $1/\delta_4$ with the values in Ref. [27] (which is $\mu_1 = 0.15$, $\mu_2 = 0.3$, $\mu_{\mathrm{f}} = 0.8$, $\lambda_{\mathrm{i}} = 0.05$, $\lambda_{\mathrm{f}} = 0.2$, $\gamma = \gamma_1 = \gamma_2 = \gamma_3 = 0.05$, $1/\delta_1 = 0.3$, $1/\delta_2 = 0.4$, $1/\delta_3 = 0.5$, $1/\delta_4 = 0.6$) in Equations (13)–(16), we got the probabilities for 4 decisions as in (17)–(20):

$$P_{S_{\mathrm{Reuse}}} = 2P_{S_{\mathrm{I}}} + 0.333P_{S_0} = 0.186389 \quad (17)$$

$$P_{S_{\mathrm{Remfc}}} = 1.33P_{S_{\mathrm{I}}} + 0.167P_{S_0} = 0.098099 \quad (18)$$

$$R_{S_{\mathrm{Recyc}}} = 2.5P_{S_{\mathrm{I}}} + 0.25P_{S_0} = 0.154506 \quad (19)$$

$$P_{S_{\mathrm{Disposal}}} = 0.5P_{S_{\mathrm{I}}} + 0.0625P_{S_0} + 0.025P_{S_{\mathrm{Recyc}}} = 0.075414 \quad (20)$$

4. Battery cycle time, SOC, SOH

In applying Markov Decision Process in Li-ion EV battery decision model, we referred some data from EV battery data file (Table 3) [27]. We compared SOH of three Li-ion EV batteries A, B and C. To estimate EV battery SOH, we had to make decision for each battery: Reuse, Remanufacturing, Recycling, and Disposal using the current status of Battery SOH and their cycle times.

In Table 3, we presented the SOC calculation of three batteries and compared with their cycle time till they reached to 1000. It is hard to find the SOH percentage of battery change till the cycle time reached to disposal, although we can calculate the decision point through the decision policy to be reuse, remanufacture, recycling and disposal for each Li-ion EV battery condition state. In Table 4, we present the battery cycle time, SOC and SOH.

After our calculation, we found the following results for remanufacturing (see, Fig. 2): for battery A, remanufacturing will be started in the cycle times 2800 (SOH 79.64%); for battery B remanufacturing will be started in the cycle times 3100 (SOH 79.60%); for battery C remanufacturing will be started in the cycle times 3300 (SOH 79.68%).

Results for recycling are as following: for battery A recycling will be started in the cycle times 4200 (SOH 69.70%); for battery B recycling will be started in the cycle times 4700 (SOH 69.76%); for battery C recycling will be started in the cycle times 4900 (SOH 69.43%). Results for disposal status condition are as followings: for battery A, cycle times was 6900 (SOH 49.50%); for battery B, the cycle times was 7750 (SOH 49.87%); and for battery C, cycle times was 7775 (SOH 49. 96%).

Table 5 shows each battery SOH percentage, cycle times and their related decision level. From Table 5 and Fig 2, in the case of EV battery A, re-use cycle time is 2700 and remanufacturing cycle time is 2,800, recycle cycle time is 4200 and disposal cycle time is 6900. We can clearly see that the battery still has a minimum of 80% capacity after 3000 cycles.

Fig. 3 and Fig. 4 show EV battery Markov decision making model by using RELEX reliability software [28] and the result of simulation, respectively.

In Fig 4, we dropped out the system availability of 0.924586. Capacity was 92.45861. The probability of battery aging was 0.470877; the probability of reuse process was 0.186389; the probability of remanufacturing process was 0.098099; the probability of recycling process was 0.154506; the probability of inspection was 0.014715; and the probability of disposal was 0.075414. Therefore, the usage life of the battery was 77.01%; recycling life was 15.45% and disposal was 7.54%.

5. Conclusion

This research presents condition monitoring techniques for battery aging system using Markov decision making model. Using

Table 3
Battery cycle time and SOC [27].

Item	Unit	1st	50th	100th	200th	300th	400th	500th	600th	700th	800th	900th	1000th
Criteria		≥100		≥90									≥70
A	Ah	17.3	16.7	16.6	16.3	16.3	16.1	16.0	15.9	15.8	15.6	15.7	15.7
	%	100%	96.7%	96.1%	94.5%	94.0%	92.9%	92.2%	92.1%	96.6%	90.3%	90.7%	91.5%
B	Ah	17.1	16.6	16.6	16.3	16.2	16.0	15.9	15.7	15.7	15.8	15.7	15.7
	%	100%	97.2%	96.8%	95.0%	94.7%	93.6%	93.1%	92.7%	91.9%	92.1%	91.4%	91.5%
C	Ah	17.2	16.7	16.6	16.3	16.2	16.0	16.1	15.9	15.8	15.8	15.7	16.1
	%	100%	97.1%	96.6%	94.8%	94.2%	93.2%	93.6%	92.7%	92.2%	91.8%	91.0%	93.6%

Table 4
Battery cycle time, SOC and SOH.

Cycle time	Org/est.	A-SOC	B-SOC	C-SOC	A-SOH	B-SOH	C-SOH
1	17.22	17.30	17.10	17.20	100.46	99.30	99.88
50	17.00	16.70	16.60	16.70	98.24	97.65	98.24
100	16.98	16.60	16.60	16.60	97.76	97.76	97.76
200	16.96	16.30	16.30	16.30	96.11	96.11	96.11
300	16.94	16.30	16.20	16.20	96.22	95.63	95.63
400	16.92	16.10	16.00	16.00	95.15	94.56	94.56
500	16.90	16.00	15.90	16.10	94.67	94.08	95.27
600	16.88	15.90	15.70	15.90	94.19	93.01	94.19
700	16.86	15.80	15.70	15.80	93.71	93.12	93.71
800	16.84	15.60	15.80	15.80	92.64	93.82	93.82
900	16.82	15.70	15.70	15.70	93.34	93.34	93.34
1000	16.80	15.70	15.70	16.10	93.45	93.45	95.83

elements in the Li-ion battery usage report for smart e bus project (e.g. battery capacity, SOC, discharge, charge, etc.), we calculated the SOH of Li-ion, and showed decision by applying Markov Decision Process for each battery condition. Moreover, we applied Relex reliability software to verify the probability of each stage. We present the SOH levels of three batteries used in the project and compare the cycle times of three EV batteries and their conditions (Table 5). Generally, in EV battery system, the battery usage drops to 70% capacity after ten years which requires recycling. According to this case study, different results are found: usage stage is 77.01%; recycling life stage is 15.45% and disposal stage is 7.54%. The batteries in this case study have a minimum of 80% capacity after 3000 cycles and can be used for the second life. The result shows that the product life span could be longer than the general warranty time

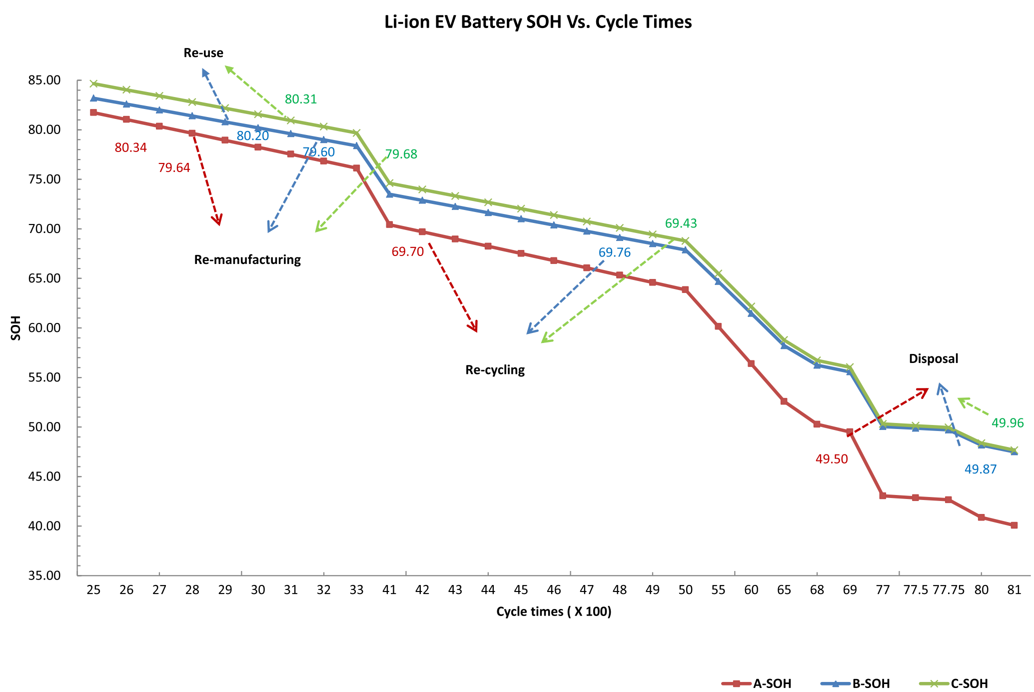


Fig. 2. EV Battery SOH and cycle times' comparison.

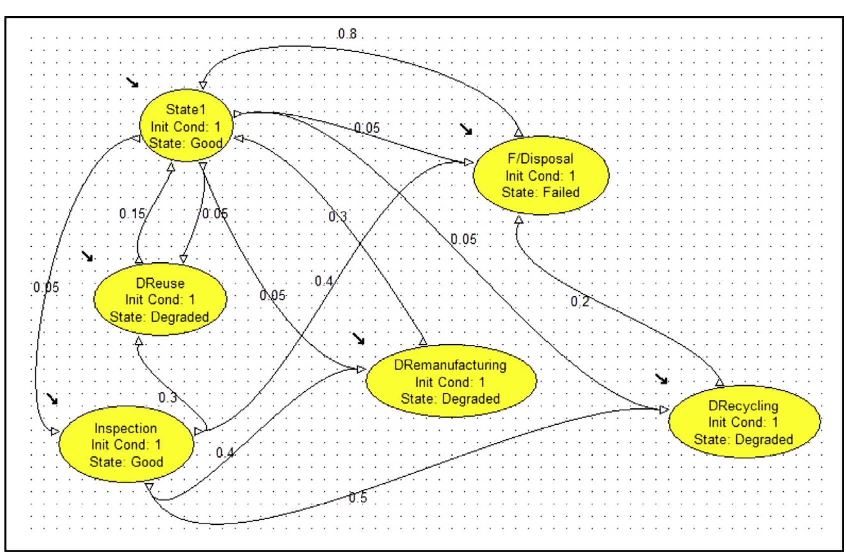
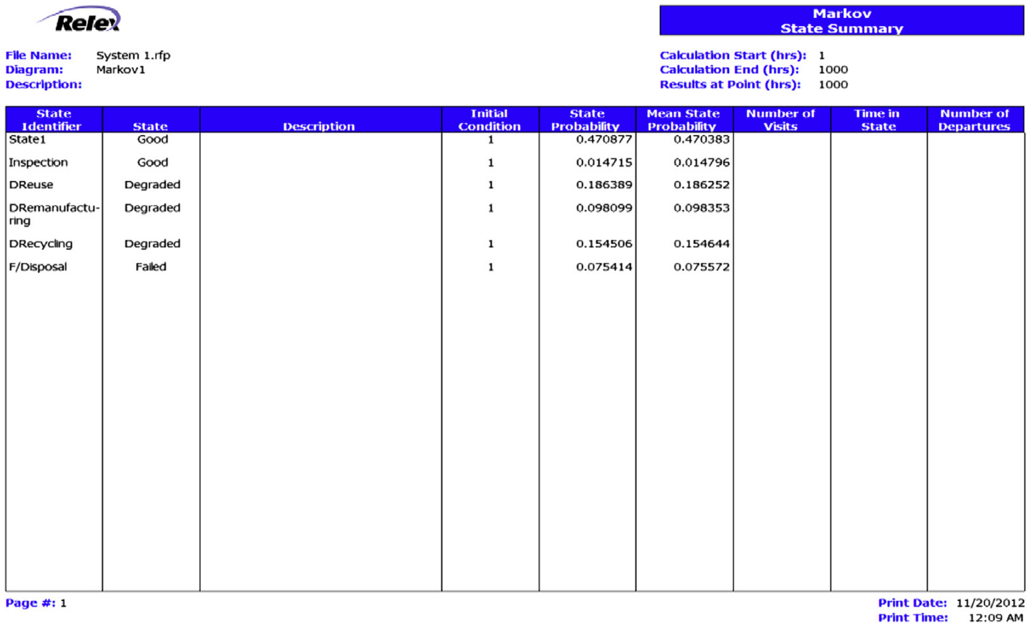


Fig. 3. EV battery Markov Decision making model with Relex reliability S/W.



Relex

Markov State Summary

File Name: System 1.rfp
Diagram: Markov1
Description:

Calculation Start (hrs): 1
Calculation End (hrs): 1000
Results at Point (hrs): 1000

State Identifier	State	Description	Initial Condition	State Probability	Mean State Probability	Number of Visits	Time in State	Number of Departures
State1	Good		1	0.470877	0.470383			
Inspection	Good		1	0.014715	0.014796			
DReuse	Degraded		1	0.186389	0.186252			
DRemanufactu-ring	Degraded		1	0.098099	0.098353			
DRecycling	Degraded		1	0.154506	0.154644			
F/Disposal	Failed		1	0.075414	0.075572			

Page #: 1

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Fig. 4. Relex reliability S/W calculation of MDP models each state probability.

Table 5
Battery status and SOH (%) with cycle times.

Battery status	A-SOH (%) (cycle times)	B-SOH (%) (cycle times)	C-SOH (%) (cycle times)
Reuse	80.34 (2700)	80.19(3000)	80.307101(3200)
Remanufacturing	79.64(2800)	79.54(3100)	79.68005(3300)
Recycling	69.69(4200)	69.75(4700)	69.43431(4900)
Disposal	49.50(6900)	49.87(7750)	49.95716 (7775)

periods in some cases. In this research, we assume the battery temperature is constant when monitoring the parameter of SOH. Generally temperature plays important role on battery performance and SOH. At this moment, we only have three batteries developed for the pilot test and do not have enough data for analyzing the impact of temperature on the SOH. It is recommended that further research should be undertaken in this area. With the proposed decision algorithm, it is possible to monitor product aging status: The inspection results provide a clue whether the system will fail or not within the next time period. Based on the current work and specific situation, different strategies can be applied to improve and to optimize the performance of EV battery in the future. The result also contributes to bring long-term environmental, social and economic value for all stakeholders involved in products manufacturing and services in the future.

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